

Ultra High Energy Cosmic Ray, Superheavy Dark Matter and Extra Dimension

Kaoru Hagiwara^{a)} and Yosuke Uehara^{b)}

^{a)} *Theory Group, KEK, Tsukuba, Ibaraki 305-0801, Japan*

^{b)} *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

Abstract

We propose a new mechanism for explaining the very long lifetime of superheavy dark matter X , which is proposed as a source of the ultra high-energy cosmic rays above the GZK cutoff (5×10^{19} eV). The singlet X particle couples to the MSSM particles only through a bulk singlet field which develops the v.e.v. in the “hidden” brane. The distance between this hidden brane and the “visible” brane naturally leads to the exponential suppression of the coupling. The X particle decays predominantly into the higgsino and higgs boson of the MSSM, and its decay spectrum is completely determined once their properties are known.

1 Introduction

Some experiments have observed [1, 2, 3, 4] cosmic rays whose energy are above the GZK cutoff ($5 \times 10^{19}\text{eV}$) [5]. The existence of such ultra high energy cosmic rays(UHECR) is a great puzzle not only for astrophysics but also for particle physics [21].

Many scenarios have been proposed to solve this puzzle. “Top-Down” scenarios typically assumes some superheavy objects like topological defects with very long lifetime [7, 8, 12], whose decay products are responsible for the observed UHECR.

It has also been proposed that UHECR may be produced from the decay of superheavy darkmatter X [10, 11, 12]. Such heavy quasi-stable particles may not overclose the universe [13] if they are gravitationally generated by inflation during the reheating epoch just after the end of inflation [14, 15].

As an origin of UHECR, its mass m_X , its lifetime τ_X and its abundance $\Omega_X h^2$ must satisfy specific conditions. It must be heavy enough to explain the energy of UHECR, it must survived until now, and the flux of X decay must be consistent with observation. These conditions lead to the constraints [21]

$$m_X \gtrsim 10^{12}\text{GeV}, \quad (1a)$$

$$10^{10}\text{yr} \lesssim \tau_X \lesssim 10^{22}\text{yr}, \quad (1b)$$

$$10^{-12} \lesssim \Omega_X h^2 \lesssim 1. \quad (1c)$$

Hence in order to realize this scenario, we should find a mechanism to make the lifetime of X long enough;

$$10^{56} \lesssim m_X \tau_X \lesssim 10^{66}. \quad (2)$$

Many mechanisms to realize this long but finite lifetime are proposed. One may restrict the decay of X by a discrete gauge symmetry [16], or one may assume that X is perturbatively stable but that it decays via non-perturbative instanton effects [10] or by quantum gravity effects [12].

In this paper, we propose a new mechanism to stabilize the superheavy object, where its decay width is exponentially suppressed because of the separation between the visible brane and the hidden brane.

2 The Model

We assume that our world is higher-dimensional (4+n dimension), and that it has at least two 3-branes. We are confined on one 3-brane (“visible brane”). In addition to our brane, another 3-brane (“hidden brane”) exists. Both the MSSM particles and the superheavy dark matter X are confined in the visible brane, whereas a gauge-singlet field ϕ propagates in the bulk.

We impose a Z_2 symmetry to forbid direct couplings between X and the MSSM particles in our brane. The Z_2 charge of the MSSM particles is 0, and that of X and ϕ is 1. Then the lowest-dimensional superpotential which is relevant for the decay of X is written as

$$W = \frac{1}{M_*} \phi X H_u H_d. \quad (3)$$

Where H_u and H_d stands for the higgs superfield of the MSSM. Let us now suppose that ϕ has a vacuum expectation value on the hidden brane. Naively, its v.e.v. should be of the order of the fundamental scale M_* . But since it appears in the hidden brane, the v.e.v. which we feel on the visible brane is not M_* . Let x be the four-dimensional coordinates, and y be the extra-dimensional coordinates. $y = 0$ denotes the location of the visible brane, and $y = y_*$ denotes that of the hidden brane. The v.e.v. $\langle \phi \rangle$ depends only on the y coordinates, and it satisfies

$$\langle \phi \rangle (y) = \langle \phi \rangle (y_*) \times \Delta_n(|y - y_*|), \quad (4)$$

where

$$\Delta_n(r) = (-\partial^2)_n + m_\phi^2)^{-1}(r) \propto \int d^n k e^{ik \cdot y} \frac{1}{k^2 + m_\phi^2}, \quad (5)$$

if the extra dimensional space is large enough as compared to the inter-brane distance r .

The suppression factor depends on the number of extra dimensions. It has the following simple form at long distances ($m_\phi r \gg 1$) [17, 18]:

$$\Delta_1(r) = e^{-m_\phi r}, \quad (6a)$$

$$\Delta_2(r) \sim \frac{e^{-m_\phi r}}{\sqrt{m_\phi r}}, \quad (6b)$$

$$\Delta_n(r) \sim \frac{e^{-m_\phi r}}{(m_\phi r)^{n-2}} \quad (n \geq 3). \quad (6c)$$

Thus, if the distance r between our brane and hidden brane is sufficiently large, the superpotential relevant for the decay of X becomes

$$W = \frac{\langle \phi \rangle (y_*)}{M_*} \Delta_n(r) X H_u H_d \equiv g_{\text{eff}} X H_u H_d. \quad (7)$$

The effective coupling constant g_{eff} is now suppressed exponentially, and hence it can be extremely small without any fine tuning. The lifetime of the X-boson(τ_X) and that of the X-fermion($\tau_{\tilde{X}}$) are essentially determined by the superpotential (7) because the soft SUSY breaking effects for the effective X couplings are suppressed by powers of $\frac{m_{\text{SUSY}}}{M_*}$. In the so-called decoupling limit where the soft-SUSY breaking mass terms are larger than the electroweak symmetry breaking scale, we find

$$\tau_X^{-1} = \tau_{\tilde{X}}^{-1} = \frac{(g_{\text{eff}} \cos \theta_X)^2}{2\pi} m_X, \quad (8)$$

where $\cos \theta_X$ is a mixing angle of the singlet sector and we denote the lighter mass eigenstate as X for brevity. The long lifetime (1b) required for the UHECR candidate is satisfied when

$$1.15 \times 10^{-33} \left(\frac{10^{13} \text{GeV}}{m_X} \right)^{1/2} \lesssim g_{\text{eff}} \cos \theta_X \lesssim 1.15 \times 10^{-27} \left(\frac{10^{13} \text{GeV}}{m_X} \right)^{1/2}, \quad (9)$$

For $m_X \sim 10^{13} \text{GeV}$, $\langle \phi \rangle (y_*) \sim M_*$ and $\cos \theta_X \sim \frac{1}{\sqrt{2}}$, the required suppression is achieved by

$$62 \lesssim m_\phi r \lesssim 75 \quad (n = 1), \quad (10a)$$

$$60 \lesssim m_\phi r \lesssim 73 \quad (n = 2), \quad (10b)$$

$$62 - 4(n - 2) \lesssim m_\phi r \lesssim 75 - 4.2(n - 2) \quad (n \geq 3). \quad (10c)$$

3 Experimental Signals

The remarkable feature of this scenario is that the superheavy dark matter X decays mainly into H_1 and H_2 , the MSSM higgs bosons and their superpartners.

Therefore once the higgs sector of the MSSM is experimentally determined (once the masses and the mixing among the higgs particles and the gauge particles are known), then the X decay spectrum is completely determined.

In the decoupling limit, the decay patterns are especially simple. If X is a boson, its decay branching ratios are

$$B(\tilde{\phi}_u^+ \tilde{\phi}_d^-) = B(\tilde{\phi}_u^- \tilde{\phi}_d^+) = \frac{1}{2} B(\tilde{\phi}_u^0 \tilde{\phi}_d^0) = \frac{1}{4}. \quad (11)$$

Whereas if X is a fermion, they are

$$B(W^+ \tilde{\phi}_d^-) = B(W^- \tilde{\phi}_u^+) = B(H^+ \tilde{\phi}_u^-) = B(H^- \tilde{\phi}_u^+) = \frac{1}{8} \sin^2 \beta, \quad (12a)$$

$$B(W^+ \tilde{\phi}_u^+) = B(W^- \tilde{\phi}_u^-) = B(H^+ \tilde{\phi}_d^-) = B(H^- \tilde{\phi}_d^+) = \frac{1}{8} \cos^2 \beta, \quad (12b)$$

$$B(Z \tilde{\phi}_d^0) = B(h \tilde{\phi}_d^0) = B(H \tilde{\phi}_u^0) = B(A \tilde{\phi}_u^0) = \frac{1}{8} \sin^2 \beta, \quad (12c)$$

$$B(Z \tilde{\phi}_u^0) = B(h \tilde{\phi}_u^0) = B(H \tilde{\phi}_d^0) = B(A \tilde{\phi}_d^0) = \frac{1}{8} \cos^2 \beta. \quad (12d)$$

Here $\tilde{\phi}$ denotes the gauge eigenstates of the higgsinos, and h, H, A, H^\pm are the MSSM higgs bosons. In the decoupling limit, the lighter CP-even higgs boson h reduces to the SM higgs boson, and all the remaining higgs bosons and higgsinos are degenerate. The W and Z bosons are longitudinally polarized.

In the real world, the mass eigenstates are the mixtures of the higgs bosons, the higgsinos and the gauginos of the same spin and charge. Nevertheless, because the X mass is far greater than any of the MSSM particles, the above decay branching fractions remain valid simply by replacing the current eigenstate as appropriate summation over the mass eigenstate contributions. W and Z decay properties are known, and we expect h, H, A, H^\pm decays to contain b and t quarks, The observed UHECR signal may be explained by protons and neutrons from these quark jets. The decay patterns of charginos and neutralinos (mass eigenstates of charged and neutral colorless SUSY fermion) depend more strongly on details of the SUSY breaking mechanism. It is likely, however, that their decays also contain W and Z bosons as well as b and t quarks. We should expect significant amount of neutrinos accompanying the UHECR events. If R-parity is conserved, then the bulk of the decaying X energy may be carried by the lightest supersymmetric particle(LSP).

4 Summary

In this paper, we propose a new mechanism to stabilize the superheavy dark matter which may be the origin of the observed ultra high energy cosmic ray.

In our scenario, the long lifetime of the superheavy darkmatter X is realized by the separation between the visible brane and the hidden brane in a large extra dimensional space.

X decays mainly into higgs and higgsino, so this scenario may be testable from the energy spectrum of decayed products. In the future it may be possible to directly detect ultra high energy neutrinos or neutralinos(LSP).

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note added

After we finished this paper, we learned from S.Sarkar that he and his collaborators proposed[19, 20] that cryptons - bound states of the fractional charges which arise in the massless spectrum of the heterotic string compactifications - may constitute the dark matter, and that they may account for the UHECR. In this scenario, the superheavy crypton lives in the hidden sector and it decays only through higher-order non-renormalizable operators. We also learned that cosmic ray spectrum from the decays of superheavy objects has been studied in detail[21, 22] by using the HERWIG event generator[23].

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